# BUOYANCY TRANSPORT VEHICLE (BTV)-A TECHNICAL EVALUATION

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Technical Report

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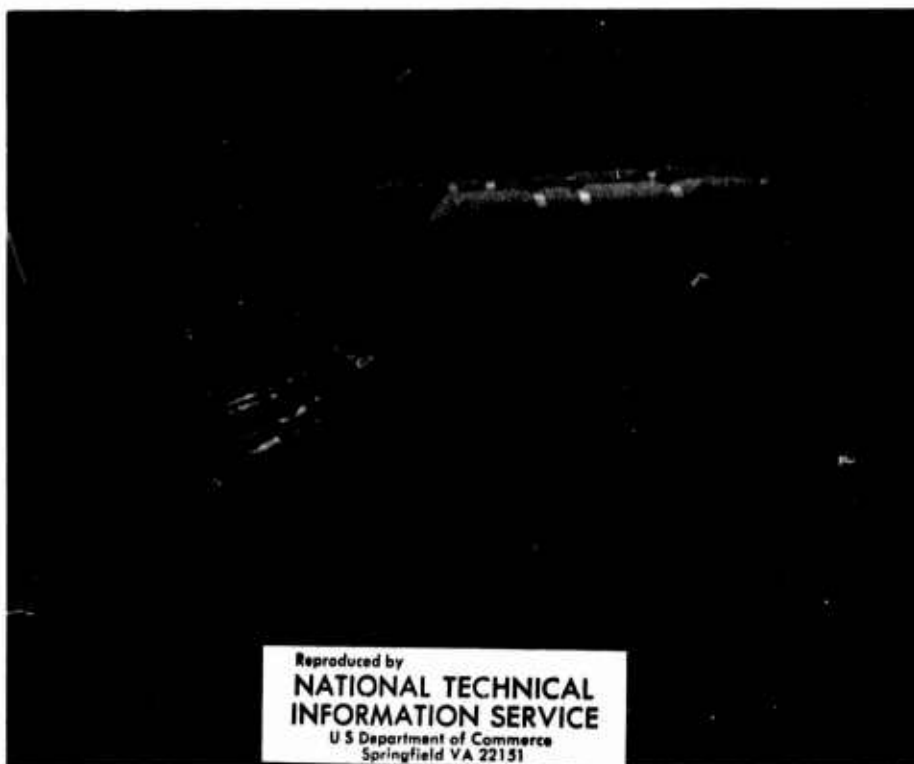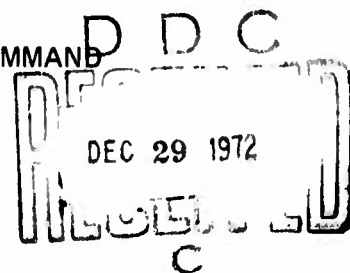
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**NAVAL CIVIL ENGINEERING LABORATORY**

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13. ABSTRACT

The potential utility of the Buoyancy Transport Vehicle (BTV) as a tool for diver construction work was evaluated. The BTV consists of a spherical variable-buoyancy tank surrounded by an aluminum pipe frame which supports the load-lifting hook, ballasting subsystem, and propulsion subsystem. It is roughly 6 by 8 by 6 feet high, has an 850-foot operating depth, a 1,000-pound payload capacity, an air weight of 1,800 pounds, and normally requires a two-man operating crew. The test program included determining basic vehicle performance plus load-handling and load-placement capabilities. Surface support and maintenance requirements were also considered. The test results indicate the Buoyancy Transport Vehicle to be effective for use in construction and salvage jobs where the diver must move large loads and precisely position them on the ocean bottom. Concept limitations include underwater visibility, endurance, and top-side support requirements.

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| 14 KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Buoyancy Transport Vehicle | | | | | | |
| Diver-controlled vehicle | | | | | | |
| Diver construction | | | | | | |
| Load handling | | | | | | |
| Load placement | | | | | | |
| Lift capacity | | | | | | |
| Speed | | | | | | |
| Maneuverability | | | | | | |
| Current | | | | | | |
| Surge | | | | | | |
| Visibility | | | | | | |
| Variable-buoyancy tanks | | | | | | |
| Electro-hydraulic power system | | | | | | |
| Hydraulic thrusters | | | | | | |
| Hydrazine gas generation | | | | | | |

IB

# CONTENTS

## INTRODUCTION

A problem frequently encountered by the working diver is that of positioning heavy objects on or near the seafloor. Current positioning techniques generally utilize lift lines from surface vessels or just plain diver muscle. Both of these methods have serious drawbacks—lines often become entangled; objects are moved blindly about by a surface operator who cannot observe directly what he is doing on the bottom; and divers attempting to relocate heavy tools and equipment, even short distances, quickly become exhausted, thereby taxing their life support systems and limiting their effectiveness. As divers go deeper, these problems become even more acute because visibility is decreased and special gas mixtures fed through umbilicals are required.

One potential solution to such difficulties is a mobile lifting device, free from surface ties, that is capable of raising heavy objects from the ocean floor and relocating them elsewhere. Lifting "bags" (inflatable balloon-like containers) have been used with some success, but because of their uncontrolled buoyancy variations with changes in depth, they have been largely restricted to operations in which the load is lifted directly to the surface.

An alternative to these techniques is a self-propelled device that uses controlled buoyancy to lift a payload. Conceptually, this device would consist of a controllable variable-buoyancy chamber with the necessary structure, energy storage, and propulsion units attached. Ideally, this device would be small and self-contained, requiring minimum surface support for launch and recovery. It would be capable of independent operation at any location where divers can operate.

The Buoyancy Transport Vehicle (BTV) was designed, fabricated, and tested to evaluate this concept. The concept was conceived under the Navy's Large Object Salvage System program and completed under the sponsorship of the Naval Facilities Engineering Command; the unit was developed by the Hawaii Division of the Naval Undersea Research and Development Center (NUC–Hawaii).[1] After completion of the vehicle and a short "builder's trial" at Pokai Bay, the BTV was shipped to the Naval Civil Engineering Laboratory (NCEL) for evaluation.

1

## VEHICLE DESCRIPTION

The BTV consists of a spherical variable-buoyancy tank surrounded by an aluminum pipe frame which supports the load-lifting hook, ballasting subsystem, and propulsion subsystem. The load-lifting hook is attached to the frame by a yoke that pivots through the center of the sphere in order to keep the center of buoyancy directly above the center of lift. Figure 1 shows the physical layout of the vehicle.

The buoyancy of the sphere (that is, water displacement) is controlled by vent and flood valves at the top and bottom of the sphere. Hydrazine gas, which is generated by passing liquid hydrazine through a catalytic generator, is used to dewater the sphere at depths greater than 150 feet. For depths less than 150 feet a high-pressure air system replaces the hydrazine gas system; at these depths the capacity of the air storage system is adequate for normal operations. Also, high-pressure air is both safer and more convenient to use than hydrazine.

Two upper pods provide additional fixed buoyancy and a nitrogen-filled battery storage area. Two lower pods house the electro-hydraulic power unit and the hydrazine fuel tank. Once neutral buoyancy is achieved, two hydraulic thrusters move the BTV horizontally and two additional thrusters move it vertically. An outlet on the BTV permits underwater tools to be connected to the BTV's hydraulic power supply.

The controls for the BTV are in a console at the stern of the vehicle. They include master power and electrical function switches and "twist-grip" handles which provide fully independent control of the hydraulic propulsion motors. The instruments include a battery voltage meter, an ammeter, an ampere-hours used gage, a hydrazine fuel gage, absolute and relative depth gages, and a load scale. Schematics of the pneumatic, hydraulic, and electrical circuits are included in Appendix A.

A crew of two operates the BTV. One diver, the operator, is responsible for the vehicle, while the other diver, the rigger, takes care of all load rigging and guides the operator in load-placement situations.

Table 1 lists the basic BTV specifications.


## TEST PROGRAM

The basic purpose of the test program was to determine the usefulness of the BTV concept and to determine and demonstrate the operating capabilities of the BTV. Consideration is given to the differences between the actual experimental BTV hardware and the concept.
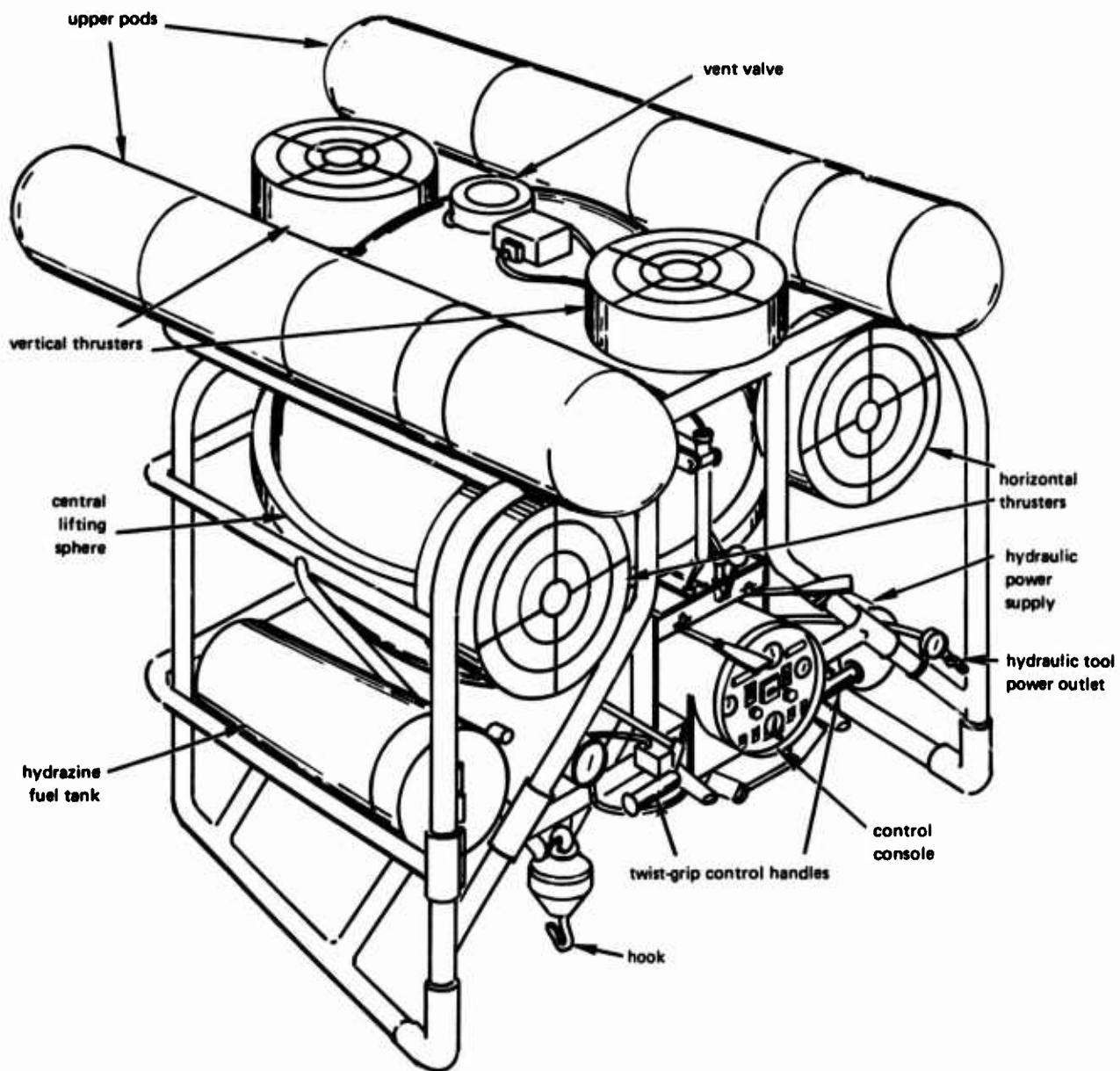
2

Figure 1. BTV with hydrazine gas generation system installed.

3

Table 1. BTV Specifications

**General:**

| | |
|---|---|
| Weight (dry) . . . . . . . . | 1,800 pounds |
| Length . . . . . . . . . . | 8 feet |
| Beam . . . . . . . . . | 6 feet |
| Height . . . . . . . . . | 5 feet 9 inches |
| Submerged speed (unloaded) . . . | 1.3 knots maximum (about 1-hour duration) |
| Maximum operating depth . . . | 850 feet |
| Cargo capacity . . . . . . . | 1,000 pounds |

**Power Train:**

| | |
|---|---|
| Batteries . . . . . . . . . | Eight independent 52-cell, 12.5-amp-hour, 100-volt sets of silver–zinc alkaline batteries, housed in one-atmosphere nitrogen-filled pods |
| Electric motor . . . . . . . | One modified Mk 34 torpedo motor; motor and hydraulic pump sealed in oil-filled pressure-compensated containers |
| Hydraulic pump . . . . . . . | Variable displacement piston pump, 10 gpm at 1,800 psi |
| Propulsion motors . . . . . . | Two horizontal and two vertical hydraulic propulsion motors; each motor rated 3 gpm at 400 rpm |
| Propellers . . . . . . . . . | 18-inch diameter, 14-inch pitch, counter-rotating |
| Steering . . . . . . . . . . . . | Steering and pitch control accomplished by independent control of four propulsion motors; no movable rudders or control planes |
| Ballast System . . . . . . . . . | Main ballast tank (central lifting sphere) dewatered using either a hydrazine gas generator system or a compressed-air system; all flooding and dewatering controlled by diver–operator using the flood and vent valves (top and bottom of sphere) and the gas generator control; enough hydrazine fuel carried to completely dewater sphere ten times at 850-foot depth; compressed-air supply provides same ballasting capability at 120-foot depth |

To accomplish this a four-phase program was developed beginning with an analysis of the BTV. The analysis was performed to predict expected performance characteristics and to determine which parameters should be studied to obtain the most useful evaluation of the concept. The design specifications and drawings, plus the results of the builder's trials, provided the basic data necessary for this effort. The parameters selected for detailed investigation were buoyancy control, speed, and maneuverability.

The second phase consisted of an extensive series of dives with the BTV in shallow water (less than 120 feet) to evaluate the vehicle in the zero payload condition. These dives provided data on buoyancy control, speed, maneuverability, endurance, ease of operator control, etc., that were used as a baseline for further tests. Phase three repeated most of the tests performed in phase two but with a variety of fixed-buoyancy payloads covering the range of weights and sizes the BTV is capable of handling. Additional tests were performed to provide data on the ability of the BTV to place a specifically oriented load at a given spot. Again, all operations were in shallow water, less than 120 feet. Phase four consisted of a realistic construction task based on the DIVERCON I experiment and data.[2]

Vehicle operators for these tests included the project engineer, assistant project engineer, project technician, and three Seabee divers from the NCEL Diving Locker.

## Buoyancy Control (Ballasting)

**Baseline.** This test was conducted by having each operator place the BTV on the bottom in the full negative buoyancy condition, bring the vehicle to neutral buoyancy, and then shut both top and bottom butterfly valves on the buoyancy sphere. The time required for this operation was recorded. This test was the first one run and was repeated intermittently for each operator throughout the test program. Average times for the six individual runs for each operator varied from 17.5 to 74.2 seconds. The overall average times, as determined from tests conducted in August 1970, February 1971, and July 1971 were 48.7, 24.6, and 38.8 seconds, respectively. Figure 2 shows the BTV during one of these tests.

It is recognized that this test does not necessarily reflect an overall proficiency in vehicle operation, but it is judged to be a reasonable and easily measured indication of operator proficiency. The decrease in average time between the first time each diver operated the vehicle in August 1970 and the time of the second test the following February indicates a definite increase in proficiency. The increase in average time in July 1971, after an inactive period of from 1 to 3 months for the operators, indicates that operator proficiency is lost when not maintained by regular practice.

5
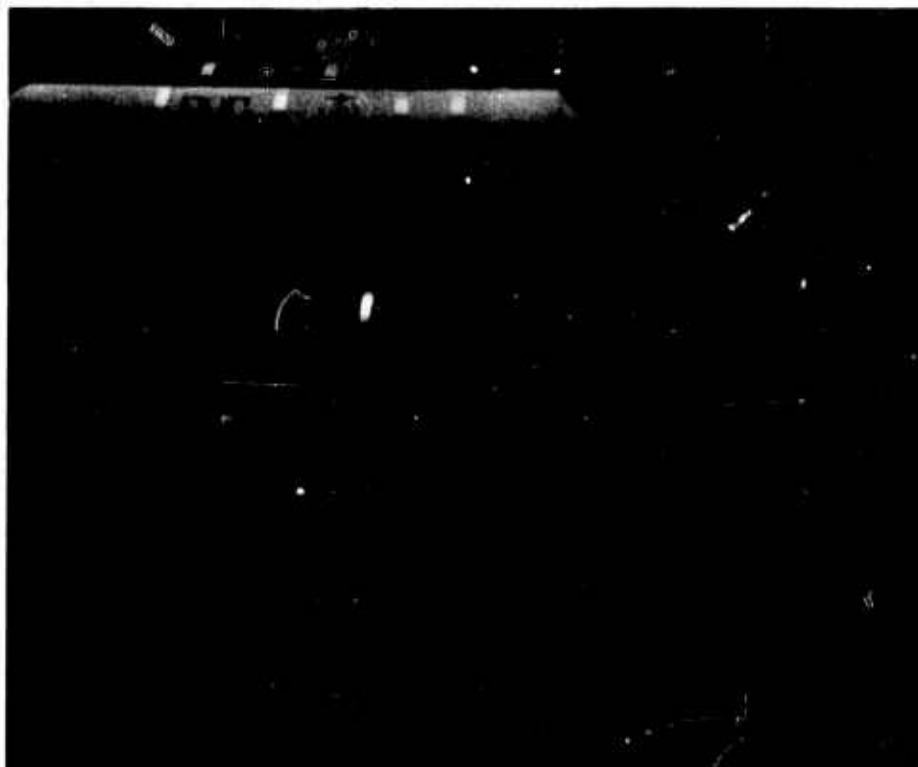
Figure 2. Baseline ballasting tests.

**500-Pound Load.** The baseline ballasting test was repeated early in the load-handling phase with the addition of a 500-pound steel weight suspended on a wire rope strap from the BTV's load hook. Both 2-foot and 10-foot straps were used to determine if operator contact with the bottom had any significant effect. Sixty-six individual tests were run with no significant difference in times attributable to load strap lengths. It should be noted that since the test load was small enough and the water clear enough the operator could easily tell when the load started to move in relation to the bottom. This visual reference of vertical motion was later shown to be a significant factor in the ability of the operator to maintain vertical position control.

**1,000-Pound Test Structure.** Additional ballasting tests were run using a 1,000-pound test structure consisting of a 46-inch-diameter by 79-inch-high vertical cylinder with a 40-inch-high, 34 x 37-inch angle iron base. The in-water weight of the structure was 936 pounds. The average time required to trim the BTV and the test structure to neutral buoyancy was 40 seconds.

6

**Speed**

Tests were conducted at NUC to determine the BTV's static thrust and vehicle drag as a function of speed. The test results predicted a maximum speed of 2.5 fps (1.5 knots) with a thrust level of 165 pounds. (See Drag Calculations in Appendix B.) When the BTV arrived at NCEL, the hydrazine deballasting system was changed to compressed air; this increased the frontal area 16%, which resulted in a 7% decrease in predicted speed to 2.3 fps. NCEL's test results, which are discussed below, gave a maximum measured speed of 2.2 fps.

Speed runs were made with various combinations of vehicle, operator, rigger, and payload. The first series of tests did not use a payload in order that the maximum possible vehicle speed could be determined. Runs were made with operator only, operator with rigger directly above, and operator with rigger to one side and below (Figure 3). The course was 100 feet long and was run in both directions to cancel out any current-induced variations. No significant difference in speed was found for the three combinations of operator and rigger, but maximum speed did decrease from 2.2 fps to 1.8 fps as the battery voltage decreased. The maximum speeds obtainable during later tests decreased due to the degradation of the electro-hydraulic system and the aging of the batteries.
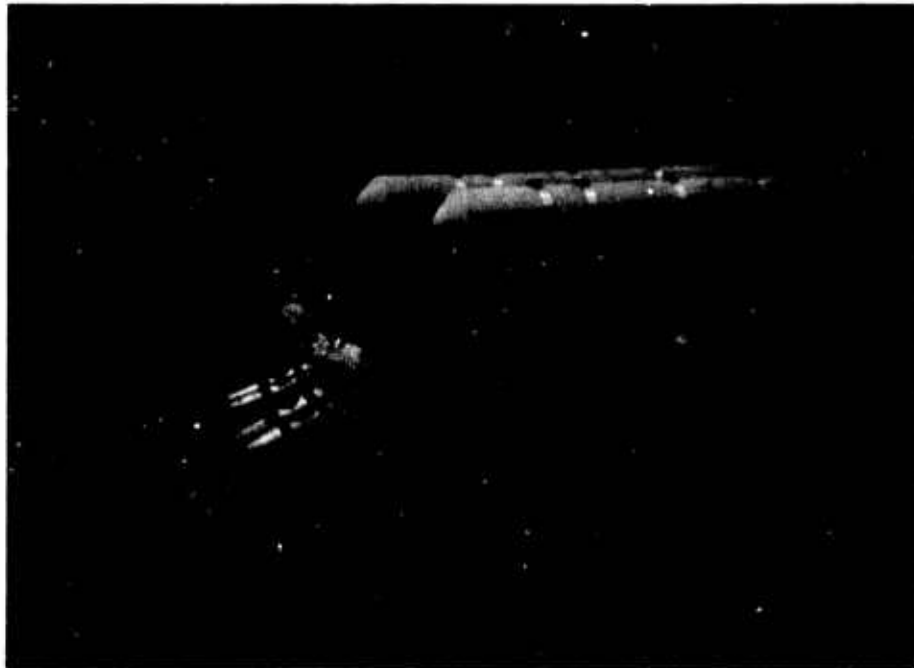


Figure 3. Speed run with rigger beside operator.

A reverse speed run over a 50-foot course was conducted with the operator only. Full speed was difficult to maintain due to problems with vehicle control in this mode. Two passes were made with speeds of 1.1 and 1.3 fps, respectively.

Speed runs were made using the 500-pound steel clump* as a payload. Because this object has very low drag, no significant change in maximum speed was expected. Four passes were made over a 50-foot course, two with the payload and two without. No significant differences were found, and a speed of 2.0 fps was attained. In addition, speed runs were made with the 1,000-pound test structure. This load has a frontal area of 20 ft², which results in a predicted speed of 1.2 fps (see Appendix B). Four passes were made over a 50-foot course, and an average speed of 1.2 fps was attained.

A measurement of the time and distance required to stop the BTV when traveling at maximum speed with no payload was made. The technique used was to approach a float marker at maximum speed and upon reaching it apply full reverse thrust until the BTV came to a stop. Two tests were made giving times of 4 and 5 seconds and distances of 2 and 2.5 feet, respectively. These numbers do not include operator reaction times, which would add 1 to 2 seconds in an operational situation. This still allows the BTV to stop from maximum velocity in a distance less than its own length.

**Load Placement**

**Hover Test.** The test started with the BTV at full negative trim on the bottom about 10 feet from the target float. The time required for the operator to trim the vehicle to neutral buoyancy and position the load hook at the float was recorded. A 2-minute period immediately followed during which the operator attempted to keep the hook at the float. Maximum horizontal and vertical excursions were recorded. Target float heights of 3 feet and 10 feet above the bottom were used to determine if operator contact with the bottom had any significant effect.

The test results show no significant difference in the time required to position the BTV for the two float heights. Excursions away from the float were slightly less for the 3-foot-high target because the operator could keep his feet in contact with the bottom. Vertical control was consistently more accurate than horizontal, probably because disturbing currents, swell motion, etc., were primarily in the horizontal plane. These tests indicate that, for the operating conditions of mild surge and light current, the BTV can maintain position within about 5 feet of the desired point over a period of many minutes. In addition, it is possible to position the vehicle at a desired point for a few seconds, given adequate operator skill.

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* See page 9 for description of clump.

**500-Pound Fixed-Buoyancy Load.** This test started with the BTV trimmed to neutral buoyancy at a position about 10 feet from the target; the 500-pound clump was on a wire rope strap on the load hook. The time required for the operator to place the clump on the target and the accuracy of the placement were recorded. Both 2-foot and 10-foot straps were used between the load and the hook. The steel clump was 10-1/4 inches by 18 inches by 18 inches, weighed 440 pounds in water, and was painted bright yellow (Figure 4). The target was a flat sheet of perforated steel 30-1/2 inches by 48 inches, painted yellow with a 10-1/4-inch by 18-inch gray rectangular area in the center as a "bullseye" (Figure 4). A series of concentric circles and radial lines allowed the observer to rapidly determine the magnitude of placement errors during the tests. Error measurements are estimated to be good to ±4 inches in the distance from the center of the target to the center of the load ($\Delta R$), and ±20 degrees in angular displacement between the load and the target ($\Delta\theta$). Problems were encountered in placing the load on the target due to the vehicle momentum overcoming the payload anchoring effect even when full down thrust was applied. Rapid flooding of the lift sphere was not used as this could cause the BTV to come down on the load and damage the vehicle.
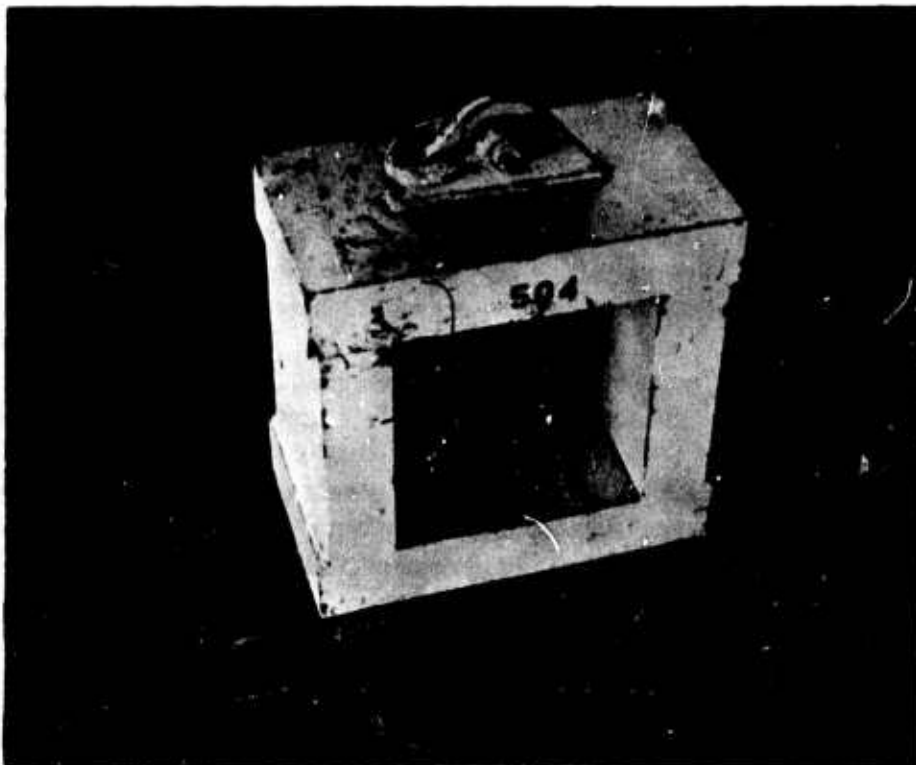


Figure 4. The 500-pound test load on placement target.

The test data show a very wide range in the time required to place the load and in the accuracy of placement. There is no correlation between the time and accuracy for any given test run; that is, short times do not correspond to poor accuracies. There is a strong correlation between the strap length (distance between payload and BTV) and placement time and placement errors. The 2-foot-long strap kept the operator close to the load and allowed his feet to touch the bottom, while the 10-foot-long strap extended the operator—payload distance and eliminated operator contact with the bottom. Use of the rigger to help position the load does provide increased control over rotational alignment, but unless he is weighted heavily enough to provide significant traction on the bottom, he contributes little to translational accuracy. The major mechanisms affecting placement accuracy appear to be current, surge, visibility, vehicle—payload momentum, and operator skill.

**1,000-Pound Test Structure on Foundation.** This test required the operator and rigger to start with the BTV trimmed to neutral buoyancy alongside a test structure. The BTV was attached to the structure, the structure was lifted and placed on the foundation, the BTV was trimmed back to neutral buoyancy, and the load was released. Times for each part of the operation were recorded.

The structure, shown in Figure 5, has been described earlier. The foundation, also shown in Figure 5, was 7 feet long by 7 feet 9 inches wide by 2 feet high. Both items were originally used in the DIVERCON I Experiment[2] as the lift device and plow anchor, respectively. Modifications to adapt them for the BTV test program included adding a platform with accompanying guide rods to the foundation to hold the structure. The guide rods were tapered to provide an effective opening, or "window," 36-1/2 inches by 39-1/2 inches. The small size of the target window, only 2-1/2 inches larger than the structure base dimensions, provided a severe positioning test. A black marking stripe provided a visual guide for proper structure—foundation alignment.

Placement times tended to be long for a number of reasons, the basic one being the small "target window." This along with a slight current, some surge, and poor visibility resulted in many passes being necessary to place the structure on the foundation. A larger target window, with tolerances on the order of ±1 foot or greater, would have allowed successful placement on the first attempt in almost all cases. During one test an air bubble was inadvertently left in the structure; this created a variable-buoyancy load with a weight variation estimated to be greater than 30 pounds between the surface and the 30-foot depth. This unplanned variation demonstrated that the BTV is not capable of maintaining vertical position control with variable-buoyancy loads of this magnitude.
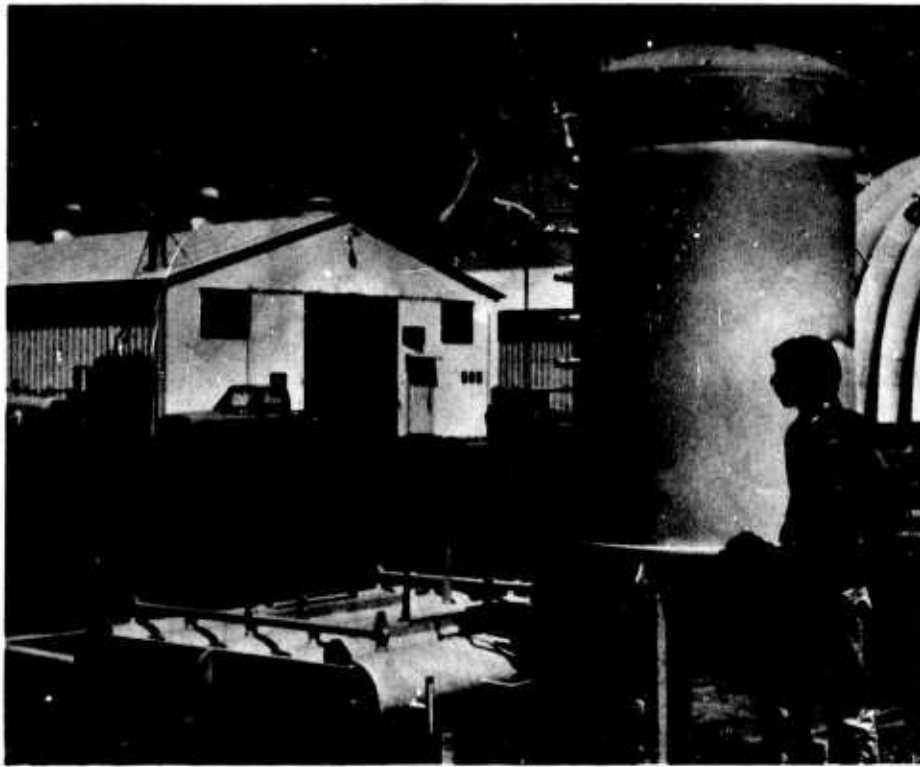
Figure 5. The 1,000-pound test structure and foundation.

**DIVERCON I Structure Assembly.** This test, also called the DIVERCON/BTV exercise, consisted of assembling the DIVERCON I structure to simulate the operational construction of a modular ocean floor structure. The DIVERCON I structure is composed of three ring-shaped modules which form a 10-foot-diameter, 10-foot-high vertical cylinder with a dome top standing on three legs on the seafloor (Figure 6). Guide rods located around the top of the lower and middle rings provide translational guidance within a target window that is 1 foot larger in diameter than the ring modules. Two V-blocks on the bottom of both the middle and top rings engage the appropriate guide rods to provide final rotational alignment. A visual mark provides rotational guidance. Initial alignment, both translational and rotational, is provided by the riggers. Rigid, constant-volume floats were utilized to supplement the lift capacity of the BTV because the in-water module weights were 1,300, 1,390, and 2,040 pounds. The constant-volume (constant-buoyancy) feature was considered mandatory as an earlier experience had shown that the BTV is not capable of maintaining vertical position control with variable-buoyancy loads.
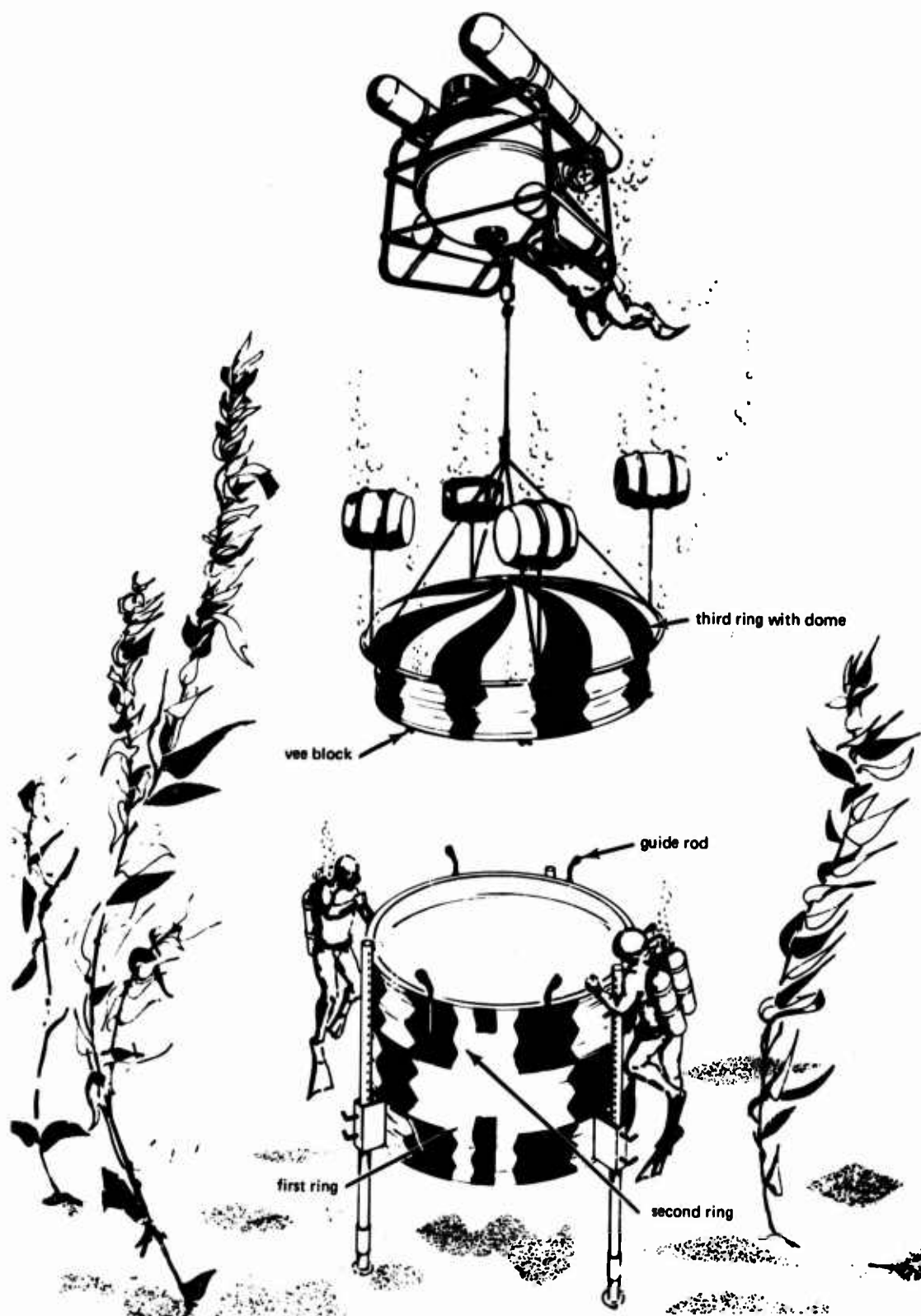
11

Figure 6. DIVERCON I structure.

Labels within figure:
- third ring with dome
- vee block
- guide rod
- first ring
- second ring

12

The assembly of this structure using a tethered, non-self-propelled lift device, a surface-powered electro-hydraulic system, and a working team of two divers was originally planned as the construction experiment for SEALAB III.[2] In preparation for the SEALAB III dive three shallow water assemblies of the structure were conducted. Average total assembly time, excluding placing the lower ring over the anchor clump, was 369 minutes. The same operations utilizing the BTV with one operator and two riggers took 105 minutes, or less than 30% of the time originally required. This reduction can be attributed to the simpler rigging that is utilized with the BTV and the much shorter time required to lift and position the modules. The middle ring was easily and rapidly emplaced because the BTV operator could see the lower ring by looking down through the middle ring. Placement of the top ring with the attached dome top was much more difficult for two reasons. First, the dome obscured the BTV operator's view of the target (middle ring). Second, a small air bubble, generated from the divers' exhaust gases, tended to build up under the dome, thereby providing a degree of variable buoyancy which made vertical positioning difficult.

## SUMMARY OF RESULTS

Each series of tests produced data on vehicle and operator performance which were analyzed to provide a measure of the performance of the BTV. These data are summarized below.

### Ballasting Rate

| System | Rate (lb/sec) | Depth (ft) |
|---|---|---|
| Hydrazine | 84 | 10 |
| Compressed air | 86.4 | 5 |

### Buoyancy Tests

| Ballasting | Number of Runs | Elapsed Time (sec) | | |
|---|---|---|---|---|
| | | Min | Max | Avg |
| Baseline, Aug 70 | 24 | 8 | 105 | 49 |
| Baseline, Feb 71 | 24 | 10 | 50 | 25 |
| Baseline, Jul 71 | 24 | 10 | 85 | 39 |
| 500-lb load on 2-ft strap | 28 | 13 | 70 | 31 |
| 500-lb load on 10-ft strap | 38 | 11 | 65 | 31 |
| 1,000-lb test structure | 6 | 25 | 76 | 40 |

## Speed Tests

| Direction | Course | Date | Number of Runs | Speed (ft/sec) | |
|-----------|--------|------|----------------|-----|-----|
| | | | | Min | Max |
| Forward | 100 feet | Oct 70 | 11 | 1.82 | 2.22 |
| Reverse | 50 feet | Nov 70 | 2 | 1.06 | 1.35 |
| Forward | 50 feet with no load | Apr 71 | 2 | 2.00 | 2.00 |
| Forward | 50 feet with 500-lb load | Apr 71 | 2 | 1.67 | 2.00 |
| Forward | 50 feet with 1,000-lb test structure | Aug 71, Feb 72 | 4 | 1.11 | 1.28 |

## Stopping Distance Tests

| Number of Runs | Distance (ft) | |
|----------------|-----|-----|
| | Min | Max |
| 2 | 2 | 2.5 |

## Hover Tests

| Target Height Above Bottom (ft) | Number of Runs | Time to Position (sec) | | | Horizontal Excursion (ft) | | | Vertical Excursion (ft) | | |
|---------|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| | | Min | Max | Avg | Min | Max | Avg | Min | Max | Avg |
| 3 | 6 | 55 | 100 | 82 | 2 | 3 | 3 | 2 | 4 | 2.3 |
| 10 | 10 | 45 | 115 | 88 | 3 | 15 | 4.6 | 1.5 | 8 | 2.8 |

## Load Placement Tests: 500-Pound Load on Target

| Strap Length (ft) | Number of Runs | Time to Position (sec) | | | Translational Error, $\Delta R$ (in.) | | | Rotational Error, $\Delta\theta$ (deg) | | |
|---------|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| | | Min | Max | Avg | Min | Max | Avg | Min | Max | Avg |
| 2 | 19 | 13 | 81 | 30 | 0 | 14 | 8 | 0 | 90 | 19 |
| 10 | 42 | 16 | 90 | 45 | 0 | 26 | 12 | 0 | 90 | 42 |

**Load Placement Tests: 1,000-Pound Test Structure on Foundation**

| Test Step | Number of Runs | Elapsed Time (sec) | | |
|---|---|---|---|---|
| | | Min | Max | Avg |
| Lift structure | 7 | 45 | 225 | 149 |
| Place structure | 7 | 66 | 425 | 229 |
| Disconnect BTV | 7 | 25 | 200 | 90 |
| Total | | 280 | 655 | 436 |

**DIVERCON/BTV Test:**

| Test Step | Number of Runs | Average Elapsed Time (min-sec) |
|---|---|---|
| Pre-assembly preparation | 1 | 20-20 |
| Lower ring assembly | | |
| Preparation and rigging | 1 | 22-00 |
| Lift and set ring | 1 | 2-10 |
| Middle ring assembly | | |
| Preparation and rigging | 1 | 17-15 |
| Lift ring | 2 | 1-20 |
| Move ring | 3 | 1-37 |
| Place ring | 3 | 2-08 |
| Top ring assembly | | |
| Preparation and rigging | 1 | 24-00 |
| Lift ring | 2 | 1-05 |
| Move ring | 2 | 4-43 |
| Place ring | 2 | 8-21 |
| Total | | 104-59 |

## DISCUSSION

The test and evaluation program for the BTV, which included 25 diving days over a 20-month period, proved that the concept of a small self-contained, free-swimming, diver-controlled lift vehicle is valid and potentially useful. In addition, the BTV was stable, easily operated, safe, and it performed the localized load handling for which it was designed quite effectively. This does not mean it could not be improved.

The ballasting tests demonstrated the capability of a free-swimming diver to control the vehicle—payload buoyancy in a satisfactory manner. However, some form of automatic buoyancy or depth control would greatly simplify and speed up the process. It would also increase the safety of the operation by decreasing the probability of an unplanned rapid ascent or descent, and it might compensate to some extent for variable-buoyancy loads.

The speed run data, combined with the subjective operating experience, indicate that a maximum vehicle speed of 2 to 2.5 fps is suitable for working in a localized area. A speed capability greater than this could result in safety problems whenever visibility is severely restricted. Speed runs using the 1,000-pound test structure with the load hook yoke locked showed no change in operating characteristics, thus indicating that the pivoting of the load hook is not necessary in future vehicles.

The hover test results indicate that the basic vehicle positioning capability is highly dependent on surge and current conditions. A steady current with less velocity than the maximum vehicle—payload speed can be corrected for with only minor difficulties; currents with greater velocities would make successful work impossible. Mild surge conditions, in the absence of currents, can be corrected for to some extent. Combinations of surge and currents in different directions can create an unworkable situation. It should be noted that such situations are also difficult for a diver to work in even without a BTV to control.

For precise positioning of loads the test data show that unless adequate load guidance mechanisms and possibly self-engaging latches are used, the best translational accuracy that can be expected is on the order of ±1 foot. This is because the vehicle—payload momentum associated with low vehicle speeds is enough to drag the payload off the desired target point even when full down thrust is applied. Without rigger assistance rotational accuracy can be expected to be within 40 degrees. This error can be greatly reduced by using the rigger to help control payload rotation during emplacement. With rigger assistance and adequate mechanical guidance highly accurate emplacement can be achieved; for example, the DIVERCON I structure was assembled to tolerances of ±1/8 inch and ±0.01 degree. Highly visible alignment guides, such

16

as fluorescent yellow or orange marks, that are easily seen by the BTV operator would significantly improve the operator's ability to determine the relative load—target position.

The assembly of the DIVERCON I structure provided additional insight into vehicle characteristics and how they would affect a field operation. The basic vehicle provides the construction diver with a local area three-dimensional load handling and positioning capability. The control system is relatively simple to operate, is conveniently located, and works well. However, in most cases, the proportional control characteristics of the thruster controls were not utilized, and an on-off control system would have been equally effective. A human factors investigation into the optimum interface configuration for a free-swimming operator and a free-swimming vehicle could provide valuable input for subsequent designs by increasing operator efficiency and safety.

Size and air weight of an operational vehicle are important factors as they determine the size of the support craft. Minimum size and air weight are necessary so that the vehicle can be used with the widest variety of support craft. Also, small, light vehicles are usually more easily controlled by the diver.

Vehicle endurance is an important consideration in any operation. A power umbilical, in addition to self-contained batteries, would allow essentially unlimited duration within the limits of the umbilical, but would still allow the vehicle to retain a completely free-swimming capability. It would also allow the vehicle to be used as a power source for tools for long periods of time without depleting the batteries. Vehicle operations with a positive or neutrally buoyant umbilical need further investigation.

Vehicle maintenance and battery charging requirements are also important considerations in an operational vehicle. These can be minimized through careful design. For example, poppet valves instead of butterfly valves for flood and vent valves should be investigated as they provide a simpler, more easily maintained system. It should be noted that the BTV was built on a limited budget specifically to test a concept; it was not optimized for endurance or maintenance characteristics.

A greater lift capability, on the order of 2,000 to 4,000 pounds, would greatly increase the versatility of a BTV-type vehicle. The capability to at least double the vehicle lift capacity using modular fixed-buoyancy devices was successfully demonstrated during the DIVERCON/BTV operation.

The operational usefulness of a BTV-type vehicle is dependent on a number of other related factors, such as adequate logistics support for the vehicle, adequate launch and retrieval capability for the weather conditions to be encountered, and adequate underwater conditions, including minimal

currents, surge, and adequate visibility. Minimum visibility limits will vary with the type of work to be done and the payloads to be moved. However, in general, operations are not safe unless the operator can see a distance equal to twice the vehicle length.

In summary, the experimental version of the BTV has shown that the concept of a small free-swimming lift device can be very useful for moving and precisely positioning relatively large objects around a localized site at diver depths. The conceptual vehicle is capable of, but is less efficient in, moving loads over long distances or to and from the surface. Specific design details of an operational vehicle should be based on the defined need and projected workload for that vehicle.

## COMPARISON WITH OTHER DIVER-SUPPORT WET SUBMERSIBLES

Various types of wet vehicles for supporting scuba divers are presented in Table 2. Swimmer Propulsion Units (SPU) provide only transportation. Swimmer Delivery Vehicles provide a limited cargo-carrying capability in addition to diver transportation. The Construction Assistance Vehicle (CAV) and the BTV are the only known diver-operated vehicles that supply power to operate the working diver's tools. The BTV complements the CAV-type vehicle in that it provides a precision load-placement capability. In fact, the BTV is the only vehicle which provides the working diver with the ability to position relatively large loads in predetermined positions on the ocean bottom.

## CONCLUSIONS

1. The BTV concept provides a useful tool that allows free-swimming divers to move and position relatively large payloads on a localized underwater construction or salvage site. It can be used, but less effectively, to transfer loads longer distances or to and from the surface.

2. The experimental BTV is stable, safe, and easily operated.

3. Vehicle and battery maintenance requirements of the experimental BTV are unacceptable for an operational vehicle. These requirements can be lowered to a suitable level by redesign.

4. The endurance of the experimental BTV is marginal for an operational vehicle.

5. Manual control of vehicle—payload buoyancy is adequate for the size of payloads handled in these tests. However, automatic control of this parameter would make the operation of the vehicle easier and safer and would allow larger capacity vehicles to be successfully developed.

6. Precise positioning of a payload on a target requires the target to be designed with guides such that the payload can latch onto them during placement.

7. A payload capacity of 1,000 pounds is minimal.

8. A maximum vehicle speed of 2 to 2.5 fps is suitable for working in a localized area with low current velocities.

9. Vehicle positioning is highly dependent on current and surge conditions.

10. Since proportional control of the thrusters is not normally necessary, the system could be replaced with an on-off control system.

11. The swinging yoke supporting the load hook is unnecessary because of the low velocity and large pendulum stability which exist for this type of vehicle.

12. The existing vehicle control system is relatively simple and easy to use. However, a human factors study of a free-swimming diver controlling a free-swimming vehicle could produce significant improvements in the next generation vehicle.

13. The size and weight of future vehicles should be kept at a minimum to reduce logistics (handling) problems.


## RECOMMENDATIONS

A prototype vehicle should be designed and built when an operational need can be adequately defined. The prototype vehicle should have the following characteristics:

1. Off-the-shelf components used wherever possible

2. Low maintenance requirements

3. Minimum 30-minute, full-throttle duration in self-contained mode with quick recharge or battery exchange capability

4. Capability to connect to a power cable to allow unlimited duration

5. Minimum 3,000-pound wet weight lift capacity

19

6. Maximum size of 8 feet by 8 feet by 8 feet

7. Maximum air weight of 2,500 pounds

8. Submerged speed (no load) of 2.5 fps

9. Independent control of horizontal thrusters utilizing an on-off control system for simplicity

10. Automatic depth or buoyancy control capability

11. Improved control system based on human factors design input

12. Fixed position load hook for simplicity

13. Electro-hydraulic propulsion system with auxiliary outlets for power tools

14. Maximum operating depth of 130 feet unless specifically stated otherwise

15. High-pressure air system for deballasting at depths less than 130 feet

16. Hydrazine system for deballasting at depths greater than 130 feet

*Photo Credit: Figures 2 and 3 were taken by the author.*

Table 2. Comparison of Wet Submersibles for Supporting Scuba Divers (From Reference 3)

| Description | General Function | Diver Support Functions | Propulsion System | Maximum Submerged Speed (knots) | Operational Time at Maximum Speed | Navigational Capability | Maintainability | Payload Capability | Tool Power | Dry Wt (lb) | L x B x H (ft) | Operating Depth (ft) | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Buoyancy Transport Vehicle— experimental | Designed to prove concept of free-swimming vehicle that provides forklift or yard crane functions at an underwater site; i.e., transport and position relatively large payloads | 1. Transport and position payloads (on bottom) 2. Power tools (limited capability) | vertical horizontal surface hover | 1.3 | 1 hour | visual | one technician full time (large part of effort is maintenance of surplus silver zinc batteries) | 1,000 lb on cargo hook | 6 gpm at 1,800 psi (oil hydraulic) | 1,800 | 8 x 6 x 6 | 850 | Steering and depth control by propulsion; buoyancy control by dewatering sphere |
| Buoyancy Transport Vehicle— (projected data) prototype | Underwater forklift/yard crane; move and position relatively large payloads | 1. Transport and accurately position large (multi-thousand pound) payloads 2. Provide hydraulic power for tools | vertical and horizontal, surface and submerged | 1.5 | unlimited on umbilical— 1 hr on batteries | visual plus limited compass | low man-hour requirements | 3,000 lb can be supplemented by modular buoyancy packages | 10 gpm at 2,000 psi | 2,500 | 8 x 8 x 8 | 130 | Steering and depth control by propulsion motors; automatic buoyancy or depth control system incorporated into design |
| Construction Assistance Vehicle— experimental | Designed as an experimental diver support platform equipped with tools, power sources, and cargo area | 1. Carry tools and cargo underwater 2. Power tools 3. Transport divers 4. Stable bottom platform | vertical horizontal surface hover turn-in-place | 2.5 | 4 hours | visual and limited compass | during operational period requires one skilled technician half time | 1,300 lb in 4 x 7-ft cargo bed or slung underneath | 12 gpm at 1,200 psi (oil hydraulic); 20 cfm pneumatic | 18,830 | 26 x 9½ x 7½ | 130 | Variable speed control; steering and depth control by propulsion, fabrication cost, $75,000 |
| Construction Assistance Vehicle— prototype | Extension of experimental model to include interchangeable work modules for drilling, excavating, cable installation, stabilization, etc. | Same as above plus: 5. Crawl on bottom 6. Translate through mild surf (3-4 ft) 7. Heavy work functions such as drilling, coring, excavating | vertical horizontal surface bottom crawl dry land surf zone | 1 to 2 | 4 hours | visual/compass; adaptable to future developments, such as transponders and pingers | designed for compatability with fleet, low maintenance, performed in the field by fleet personnel | 2,000 lb in cargo bed or lift | total power to vehicle ~20 to 50 hp; power can be directed to diver tools (hydraulic) | 10,000 to 15,000 | — | diver limited | All specifications preliminary, derived for interpolation with performance of existing vehicle; both land and underwater final specifications will follow preliminary design |
| Swimmer Propulsion Units | Designed for transportation of a single diver, commercially available units mostly designed for recreation | 1. Transport divers 2. Visual survey or photography | horizontal surface | 2 to 3 | 1-4 hours | usually direct visual | relatively low maintenance because of simplicity of vehicle | none | none supplied | 50 to 100 | 3 x 1 x 1 | 150 | Primarily designed as a propulsion device; cost: $400 and up |
| Swimmer Delivery Vehicle: "Shark Hunter," commercial | Designed to transport two divers, tools, and limited cargo to and from underwater site | 1. Carry divers and tools to underwater work site 2. Survey bottom | horizontal surface | 2 to 4 | 1-3 hours | visual | low maintenance because of simplicity of structure and components | usually inside vehicle | none supplied | 1,200 to 2,500 | 16 x 8 x 5 | 150 to 300 | Step speed control; steering and depth controlled by planes and rudders, cost: $500,000 |
| Swimmer Delivery Vehicle | Several commercial models available; military models provide increased speed, endurance, cargo, and cost | — | — | — | — | — | — | 100 to 300 lb; 5 to 10 ft³ | — | — | — | — | — |
| Surface Support Platform | Ship or other moored platform with compressors, generators, etc., mounted on deck | 1. Support working diver 2. Tools and lifting positioning limited by sea state 3. Divers burdened by umbilicals | Surface and possibly a sled towed underwater for survey | N/A | N/A | standard surface ship techniques | standard ship maintenance, performed by regular diver | ship lift capacity | limited only by size of umbilical diver can carry | N/A | N/A | N/A | Support of diver limited by safety factors relating to sea state and umbilicals |

21

Appendix A

SCHEMATICS OF BTV SYSTEMS
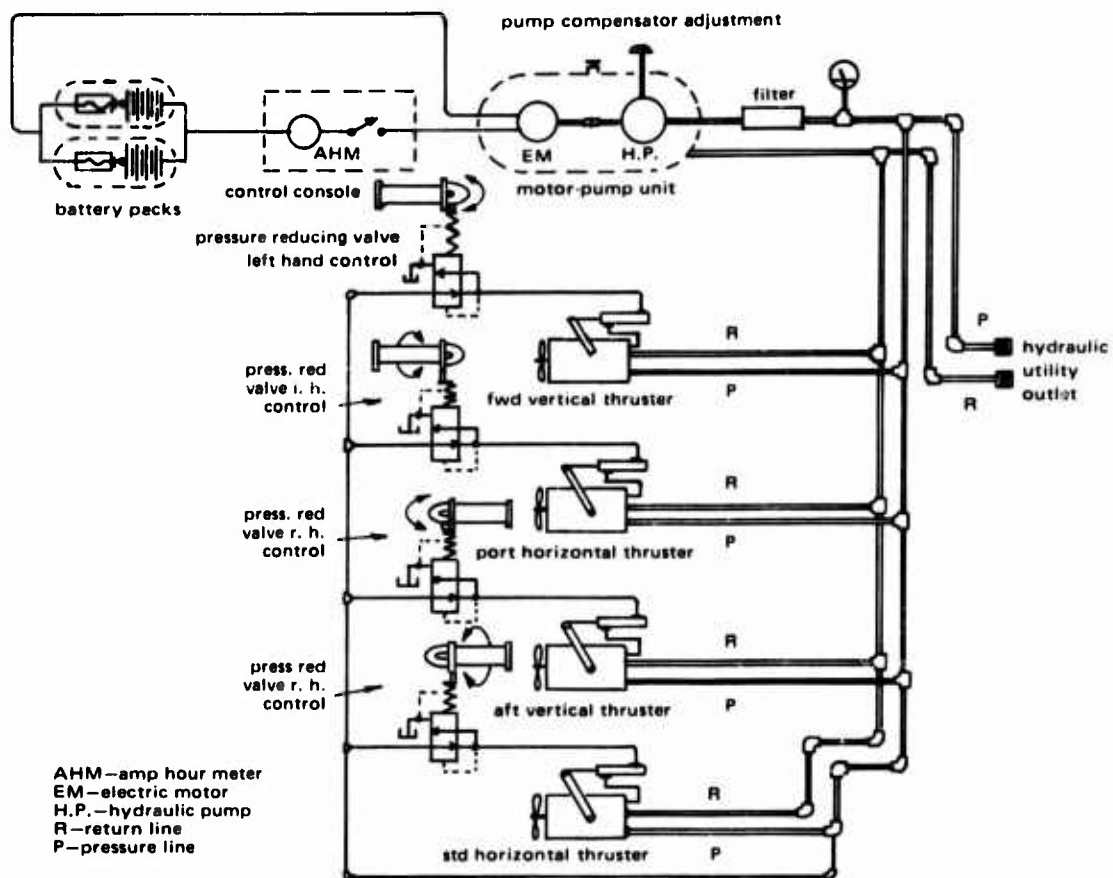
Figure A-1. Hydraulic propulsion system with utility outlet for hydraulic tools.
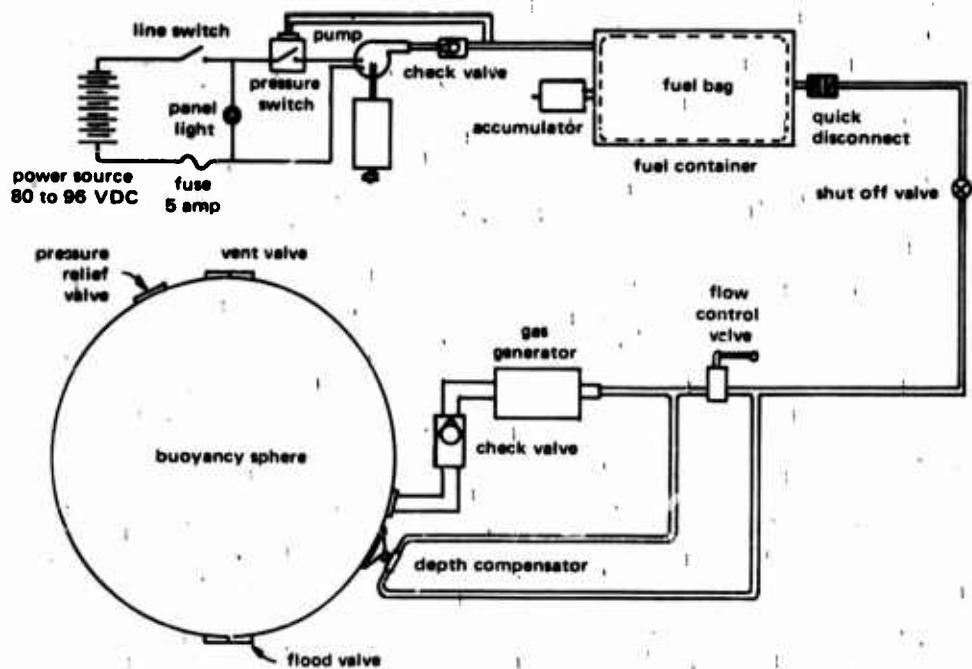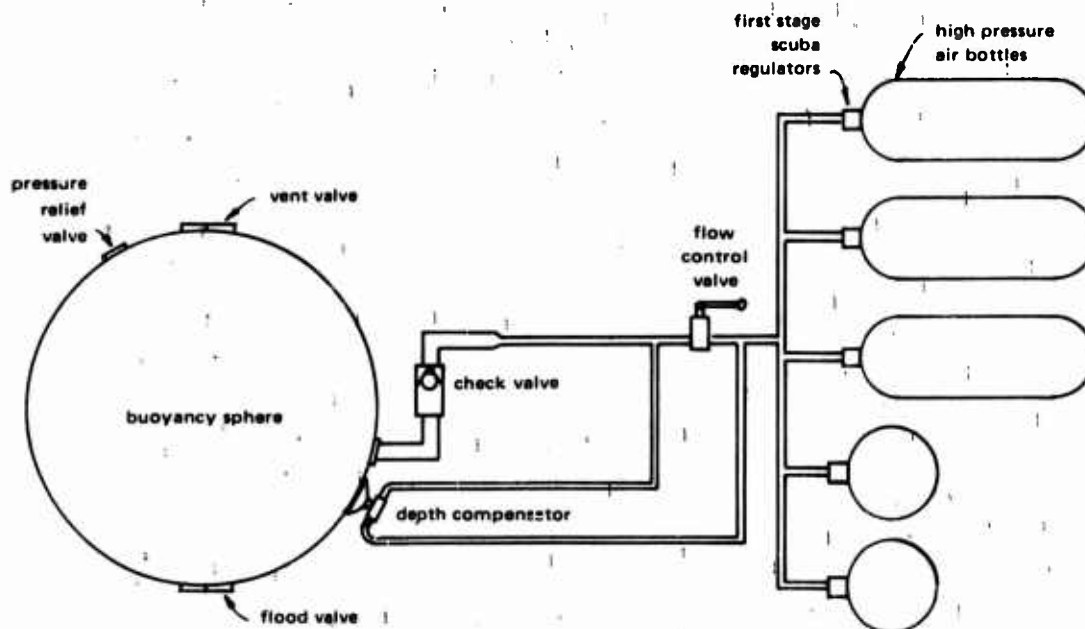
Figure A-2. Hydrazine dewatering system.



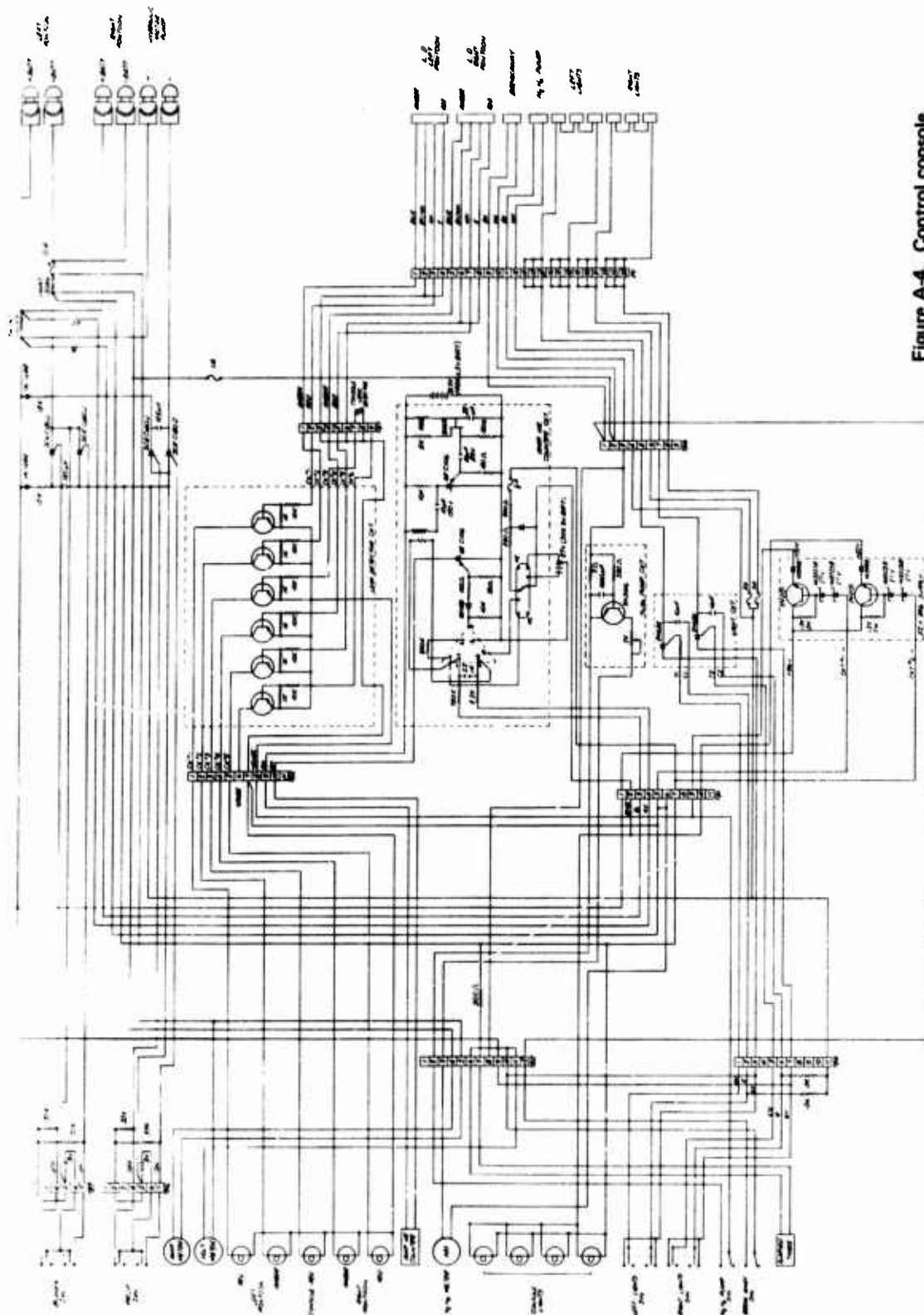Figure A-3. High-pressure air dewatering system.

25

Figure A-4. Control console.

## Appendix B

## DRAG CALCULATIONS

For constant speed conditions the BTV motion can be described by the equation:

$$|F| = \frac{1}{2} \rho A C_D V^2 \qquad \text{(B-1)}$$

where  $|F|$ = magnitude of the thrust generated by the propellers

$\rho$ = mass density of seawater

$A$ = frontal area of the BTV

$C_D$ = drag coefficient of the BTV

$V$ = velocity of the BTV

Tests performed by NUC showed a peak minimum thrust of 165 lbf from the horizontal thrusters with the BTV held motionless. NCEL measurements gave a vehicle frontal area of 27.4 ft² with the high-pressure air system installed or 23.6 ft² with the hydrazine system installed. Phase two tests gave a peak minimum forward velocity of 2.2 fps and an average minimum forward velocity of 2.0 fps with the high-pressure air system installed. Solving Equation B-1 for $C_D$ gives

$$C_D = \frac{|F|}{\frac{1}{2} \rho A V^2} \qquad \text{(B-2)}$$

Assuming the total thrust available from the horizontal thrusters was the same during the NCEL and NUC tests, Equation B-2 gives a value for $C_D$ of:

$$C_D = \frac{165 \text{ lbf}}{\frac{1}{2} \left(2.0 \frac{\text{lbf-sec}^2}{\text{ft}^4}\right) (27.4 \text{ ft}^2) \left(2.2 \frac{\text{ft}}{\text{sec}}\right)^2} \cong 1.24$$

The predicted top speed of 2.5 fps obtained by NUC from drag and static thrust data (Figure B-1) for the BTV with the hydrazine system installed can be verified by rewriting Equation B-1 in the form

$$V^2 A = \frac{|F|}{\frac{1}{2}\rho C_D} \qquad (B-3)$$

The right-hand side of Equation B-3 can be considered constant; therefore,

$$V_1^2 A_1 = V_2^2 A_2$$

where the subscripts 1 and 2 refer, respectively, to the BTV with hydrazine or high-pressure air systems installed. Solving for $V_1$ gives

$$V_1 = V_2 \sqrt{\frac{A_2}{A_1}} = 2.2 \sqrt{\frac{27.4}{23.6}} = 2.4 \text{ ft/sec}$$

This corresponds well with the NUC predicted 2.5 fps when the potential inaccuracies in the original data are considered.

The predicted speed of the BTV plus payload can be calculated by using Equation B-3 and taking into account the changes in thrust output and frontal areas. Equation B-3 can be rewritten in the form

$$V_1^2 = \frac{|F_1|}{\frac{1}{2}\rho A_1 C_D} \qquad (B-4)$$

Thus,

$$\frac{V_1^2 A}{|F_1|} = \frac{V_2^2 A_2}{|F_2|}$$

and

$$V_1 = V_2 \sqrt{\frac{|F_1|}{|F_2|}\left(\frac{A_2}{A_1}\right)} \qquad (B-5)$$

To calculate the predicted speed of the BTV carrying the 1,000-pound test structure the following parameter values are used:

$V_2$ = 2.0 fps, average maximum vehicle speed

$F_1$ = 120 lbf, from NCEL tests shortly before speed runs with test structure

$F_2$ = 165 lbf, thrust level at which $V_2$ was measured

$A_1$ = 53.4 ft$^2$, total frontal area for BTV plus test structure

$A_2$ = 27.4 ft$^2$, frontal area for BTV only

Using Equation B-5, the predicted speed, $V_1$, is:
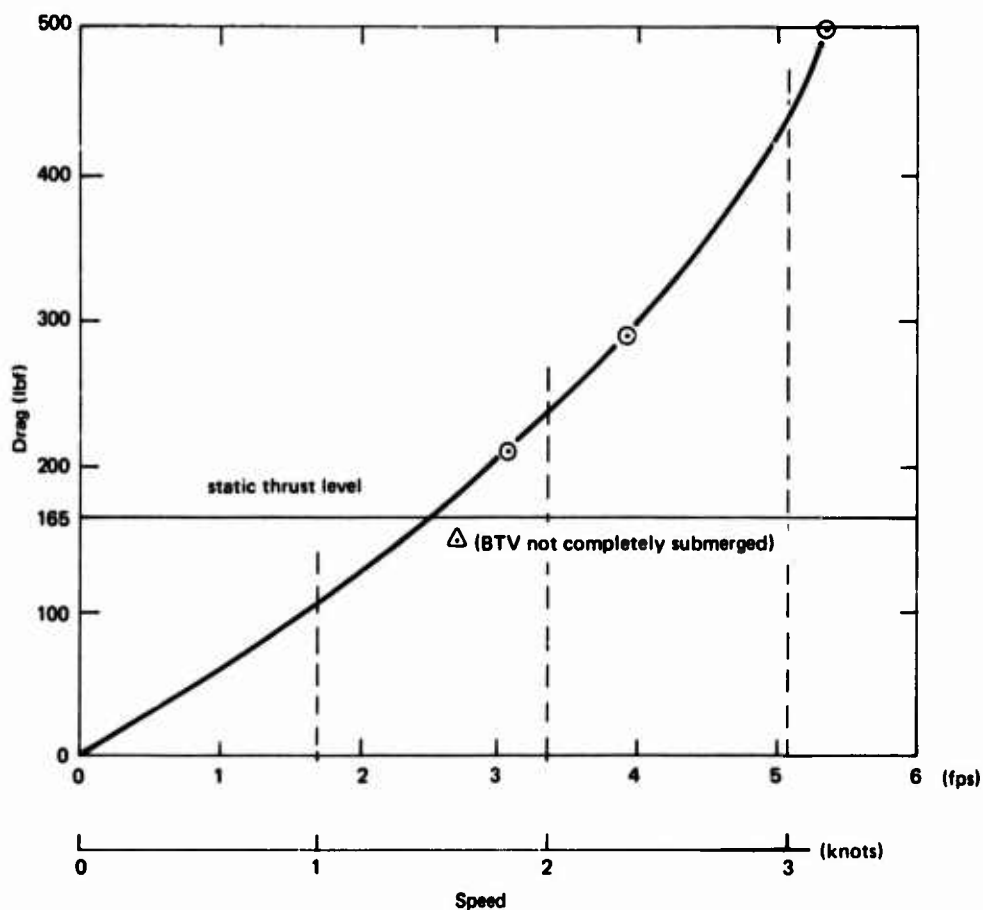
$$V_1 = 1.2 \text{ fps}$$



Figure B-1. Drag and static thrust of BTV.

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